U.S. EPR
Design Certification Review
RLBLOCA Methodology Audit

AREVA NP Inc. and the NRC
September 15, 2009

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AREVA

Objective

Describe the proposed strategy for addressing NRC concerns, and thus reduce the magnitude of PCT penalties, while preserving overall DC review schedule.

Agenda

- Accumulator Nitrogen Injection — L. Schor
  - Status of Critical Flow Evaluation
  - Sensitivity Study on Blocking Nitrogen
- Accumulator Minimum Temperature — E. Moore
- RODEX3 — B. Dunn
  - RODEX3A Issues
  - Average Core
  - FUELK
- Lower Plenum Refill — C. K. Nithianandan
- Decay Heat — B. Dunn

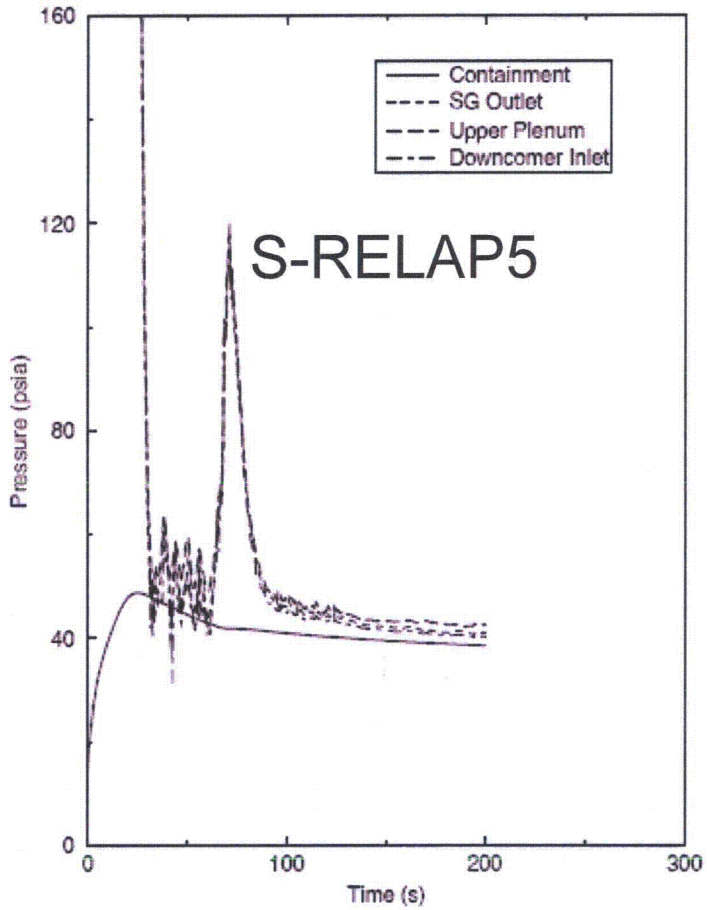
Nitrogen Injection – Critical Flow

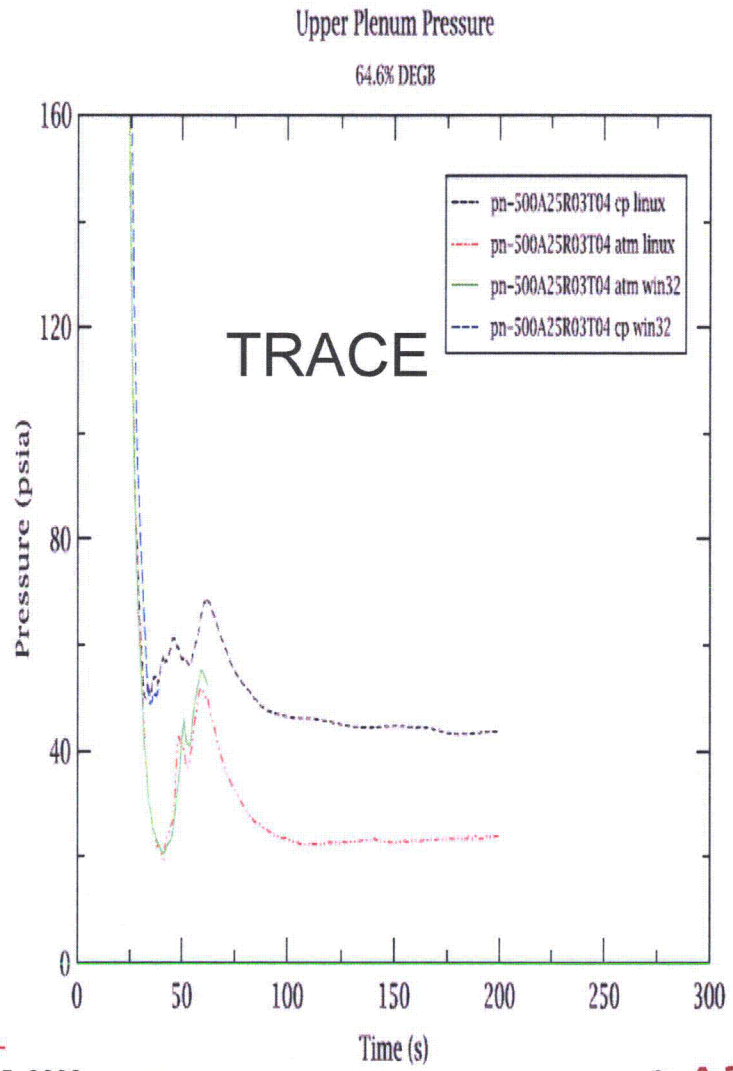
- **NRC RLBLOCA Topical Report Major Issue #2**
  - **S-RELAP5 code does not appropriately predict the critical flow with the presence of nitrogen under certain conditions.**
    - IMPACT: Higher-than-expected RCS pressurization prediction for certain cases
- **To address this issue AREVA initiated a Condition Report Review**
- **The Condition Report has been completed and closed**
  - **The S-RELAP5 critical flow was determined to adequately model non-condensable and mixed gases**
  - **More details will be presented in a subsequent audit**

Nitrogen Injection

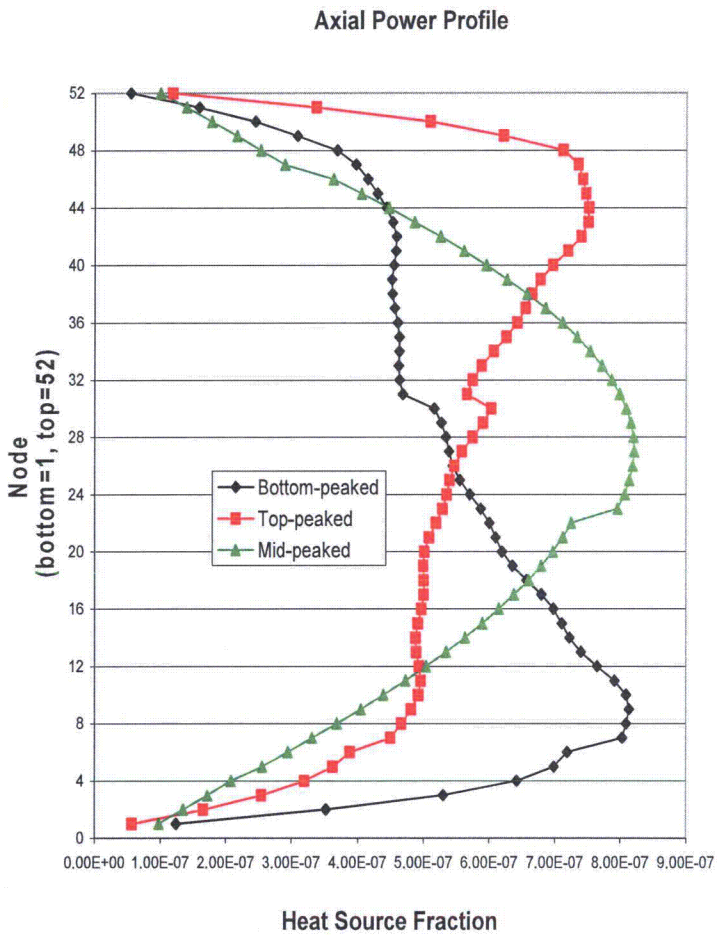
- **To address the system pressure results**
  - **The cases submitted as part of sample problem in ANP-10278P were rerun with no nitrogen injection.**
    - Accumulators isolated when close to empty.
    - Similar to a study conducted in response to RAI-28 on ANP-10278P

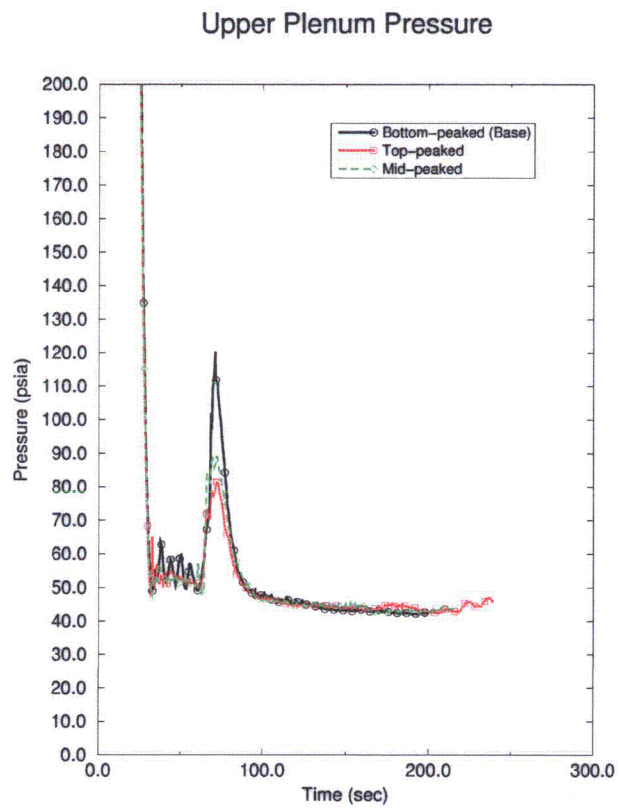
Nitrogen Injection – Comparison of the Magnitude of Pressure Spike Co



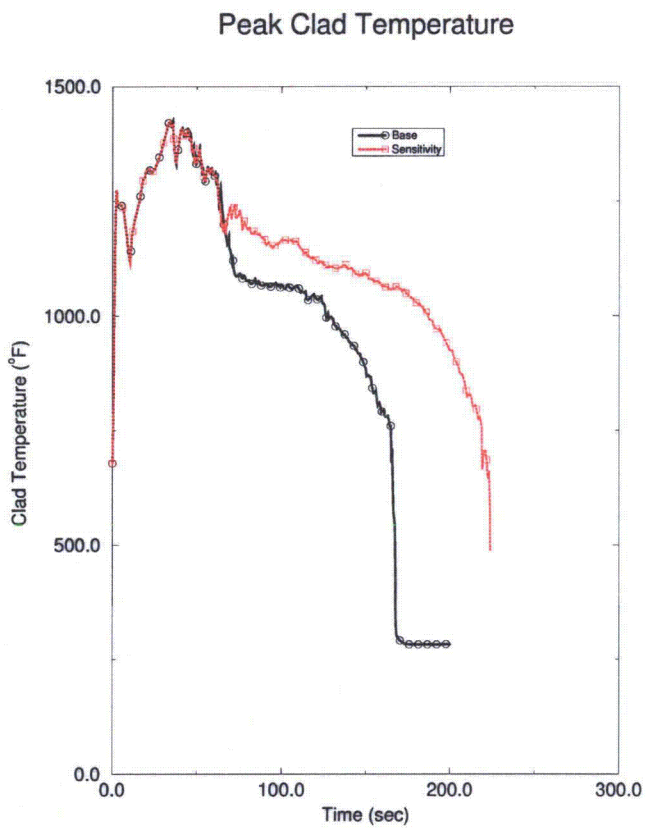


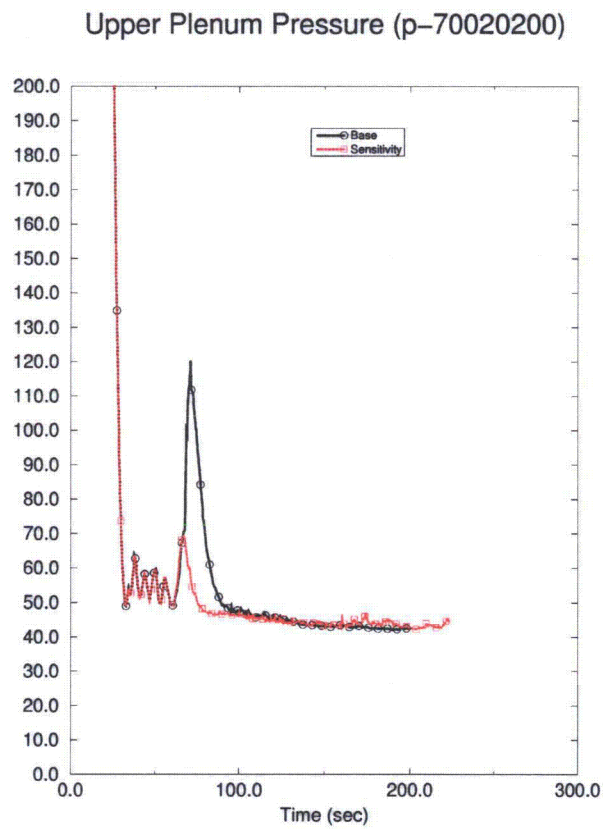
Nitrogen Injection - Effect of Axial Skew on Upper Plenum Pressure



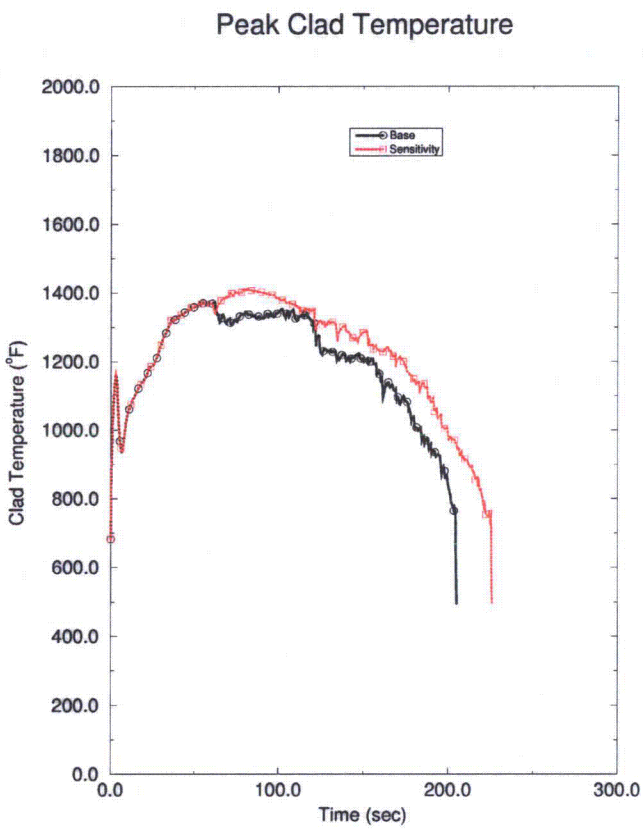


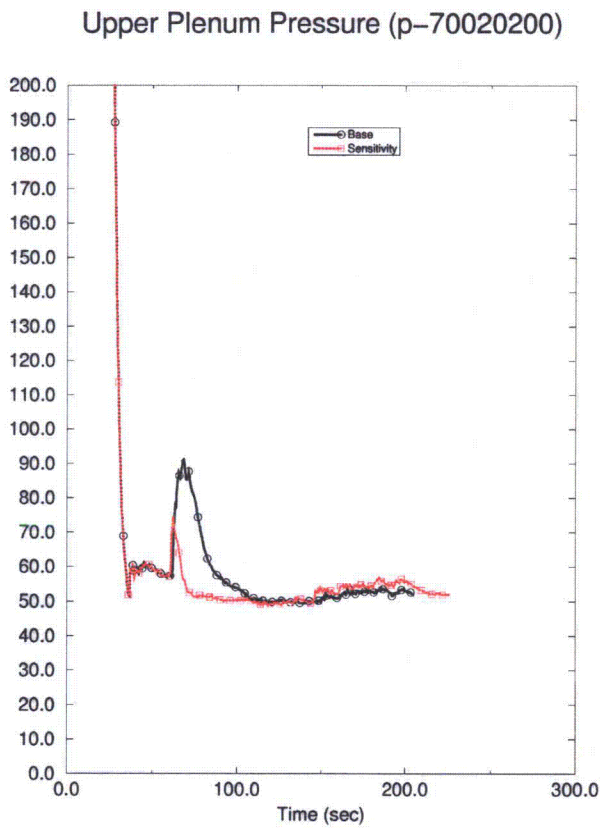
Nitrogen Injection - Case 44



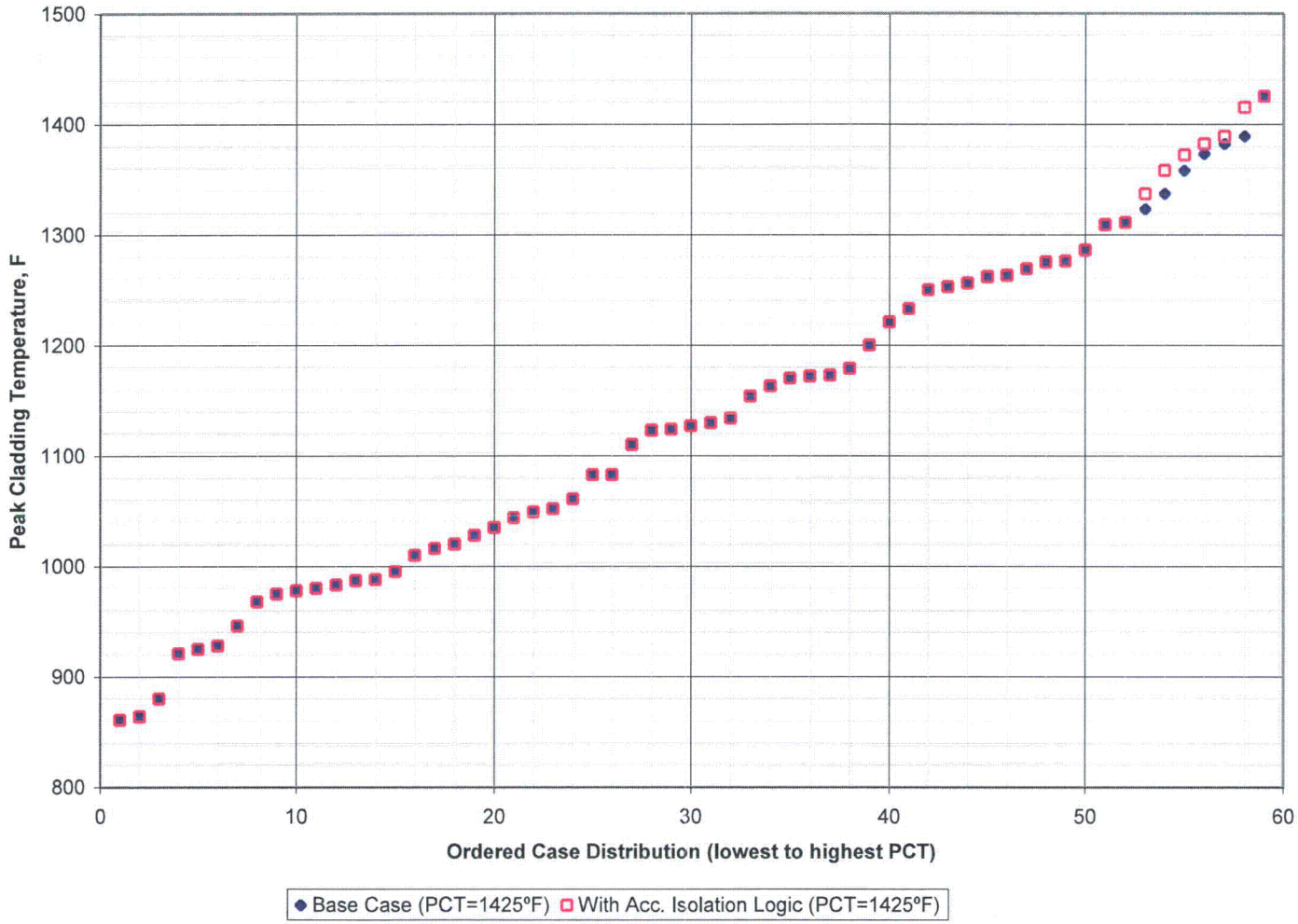


Nitrogen Injection - Case 18





Nitrogen Injection – Sorted Results for 59 Cases



Nitrogen Injection

- Conclusions
  - Critical Flow is correct when nitrogen present
  - The overpressurization is due to increase in Nitrogen volume in the accumulator
  - For conservatism, accumulator is disconnected at the time of nitrogen injection
  - The overall impact on PCT is not significant

Accumulator Temperature

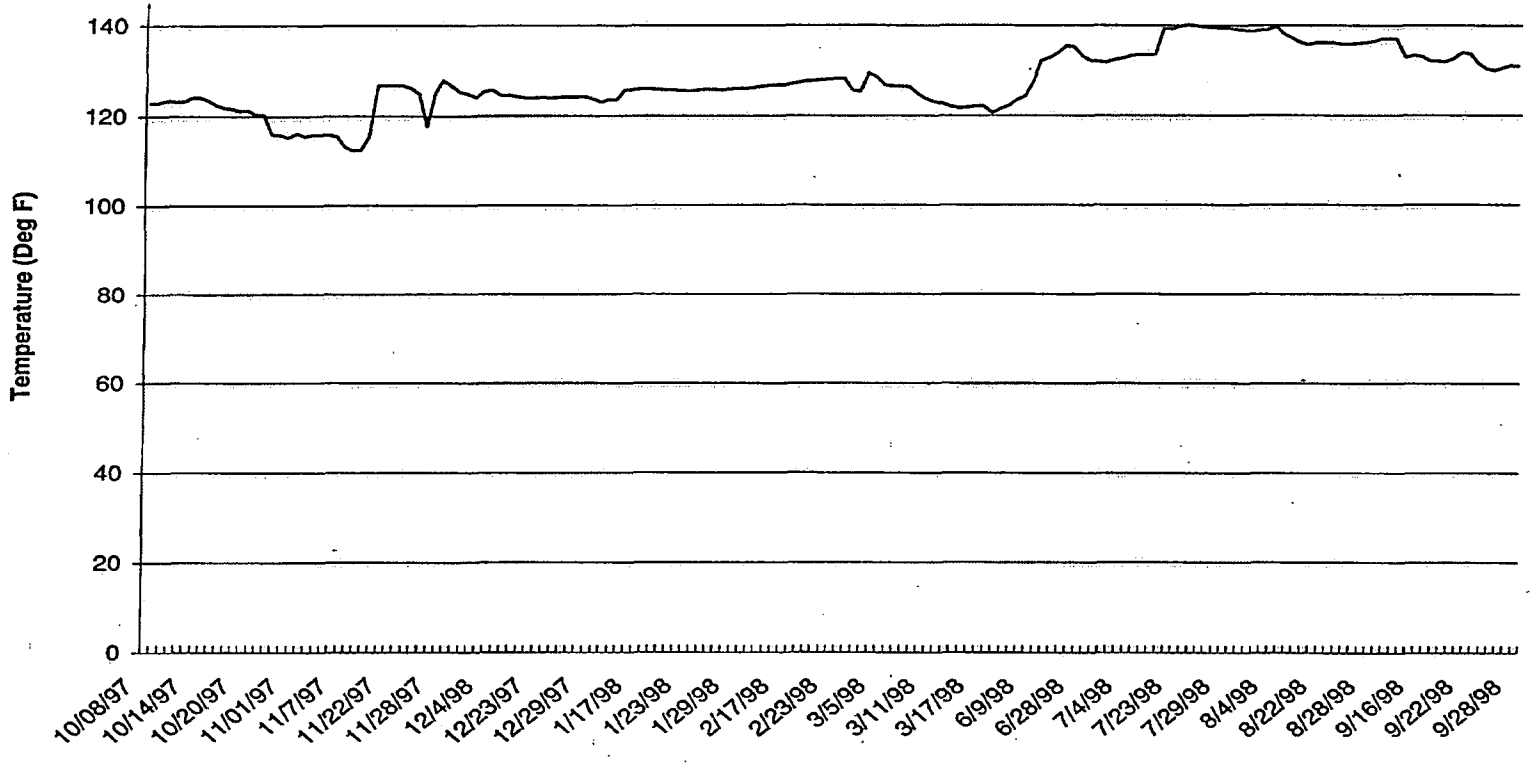
- RLBLOCA model applies the sampled value of the containment temperature to:
  1. Accumulators
  2. Containment vapor and liquid
- RAI-24 on ANP-10278P: The containment temperature is sampled from 59°F to 131°F.

Accumulator Temperature

- Lower bound of containment temperature sampling range is 59°F
  - Technical Specification minimum temperature for IRWST (Technical Specification Surveillance Requirements (SR) 3.5.4.1).
- It was proposed that 59°F is too low for a best-estimate plus uncertainties analysis.
  - An operating PWR with a large, dry containment uses a value of approximately 80°F for the lower bound of the containment temperature sampling range.
  - ANP-10299P uses 86°F, which is the maximum temperature for the space below 7.5 ft.
  - Seabrook Plant recorded containment temperatures of 110-140 F

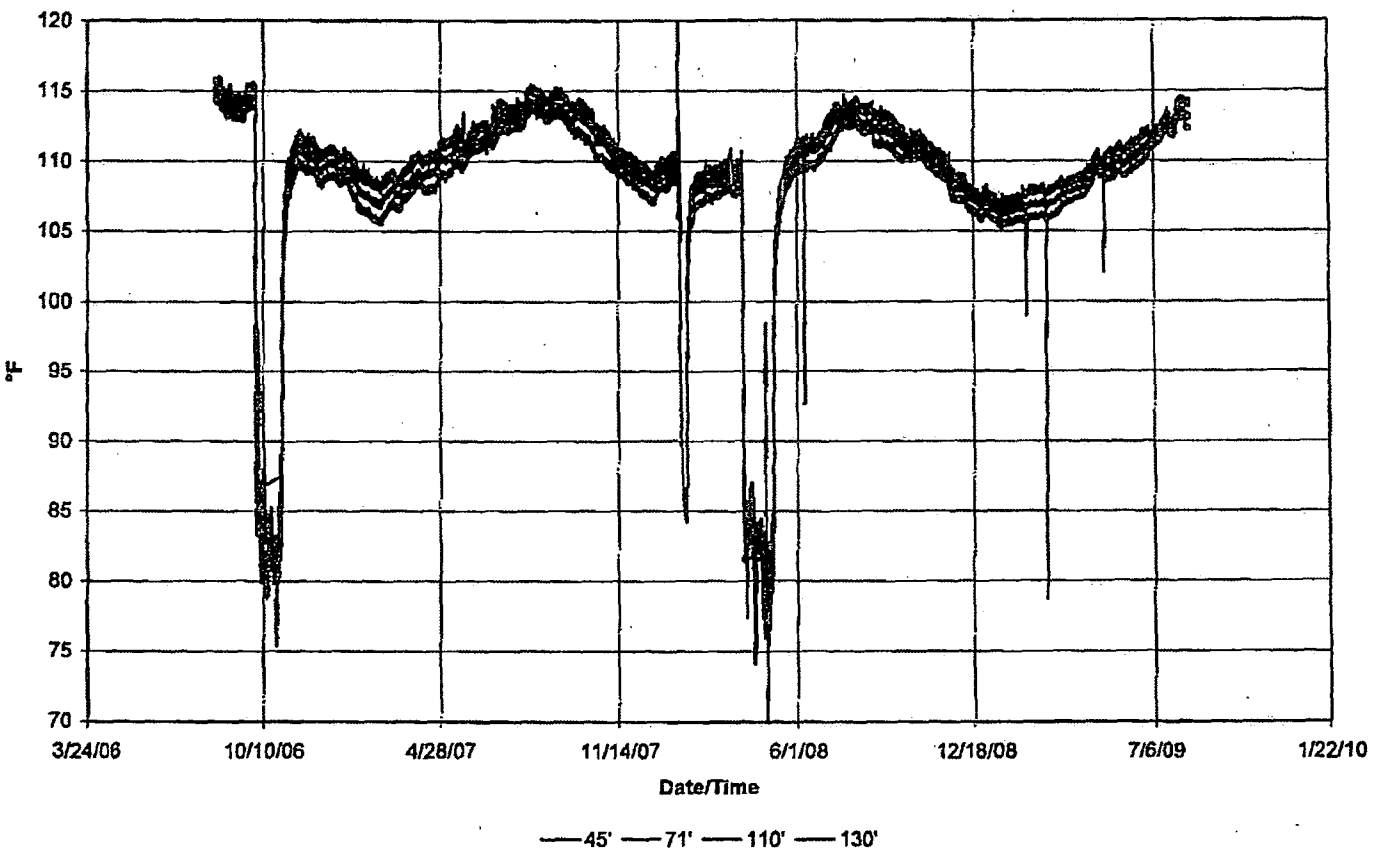
Accumulator Temperature

Vermont Yankee Containment Temperature, recorded daily from 10/08/97 to 9/28/98



Accumulator Temperature

Seabrook Containment Temperature



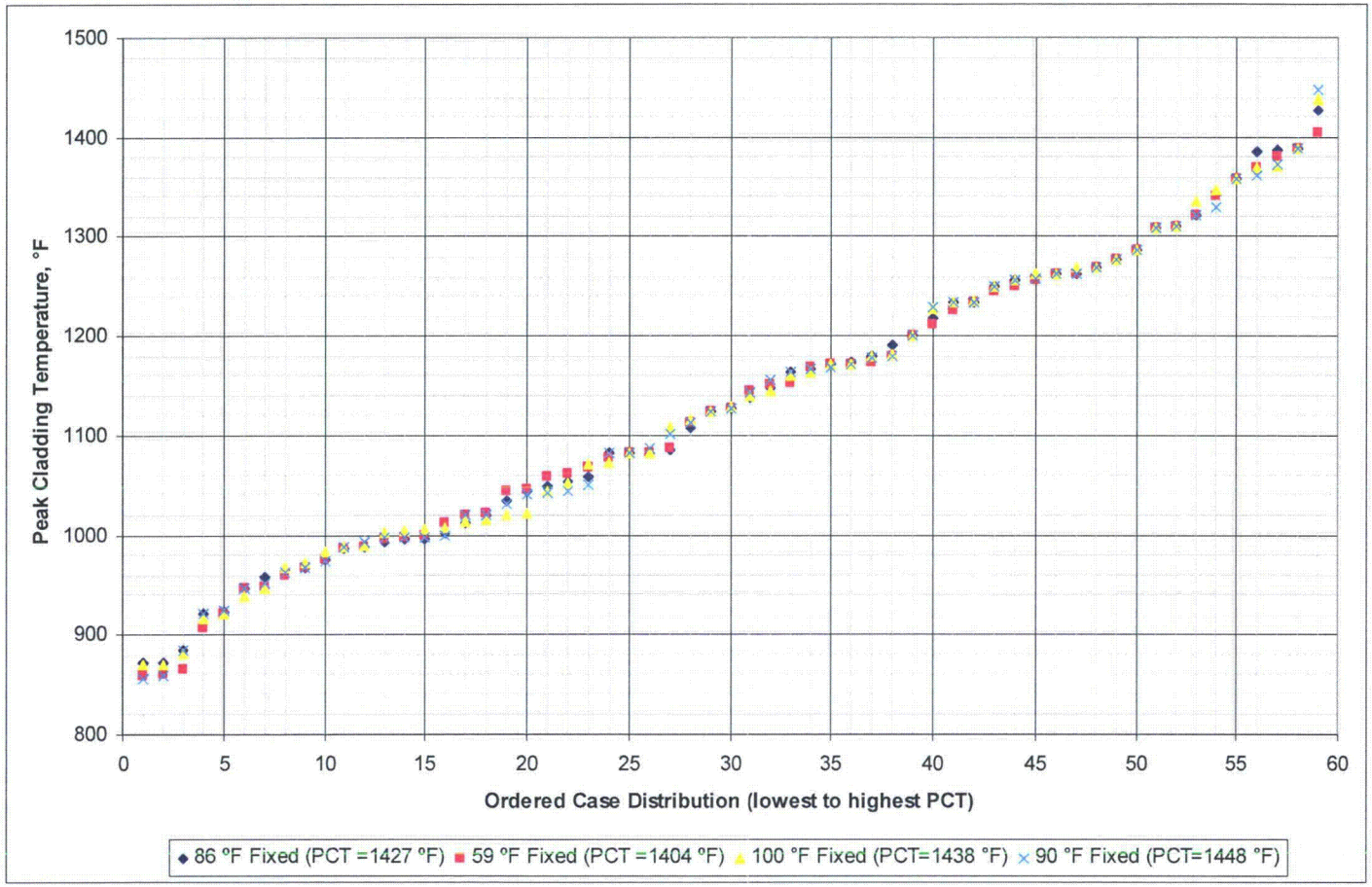
Accumulator Temperature

Basis for Lower Bound of Sampling Range

- Lower bound = 90.5°F
  - Palisades Nuclear Plant's lower bound temperature is nominal operating temperature of accumulator's, 80°F
  - U.S. EPR's min and max IRWST temperatures are 59°F and 122°F, respectively. Average of the temperatures yields 90.5°F
- Lower bound = 100°F
  - Seabrook Nuclear Plant recorded containment temperature daily for a year
  - Max. and min. recorded temperatures were in a narrow band, 105-110°F
- U.S. EPR's lower bound 100°F

Accumulator Temperature

PCT Sensitivity to Proposed Temperature Distribution



Accumulator Temperature

▶Conclusion

- ◇ Examination of plant data shows 100°F reasonable lower range
- ◇ The overall impact on PCT is not significant

RODEX3 Topics

- RODEX4 Data Base
- Sensitivity Studies on CFL Temperature
- FUELK for Transient
- Review of Average Core Treatment Plans

RODEX3 Comparison to Data Base

Fuel Centerline Temperature Delta of Adjusted RODEX3A calculations to Data

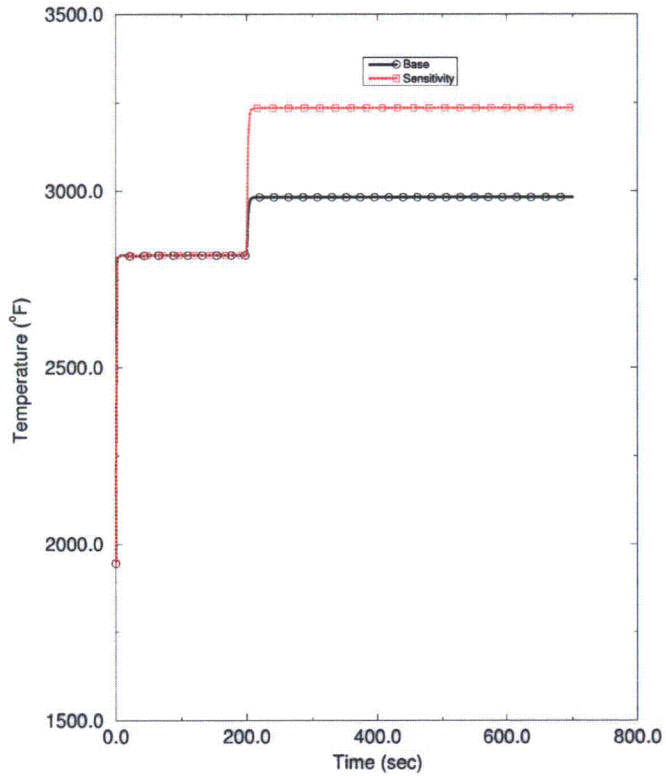
0

RODEX3 Comparison to Data Base

RODEX3 Comparison to Data Base

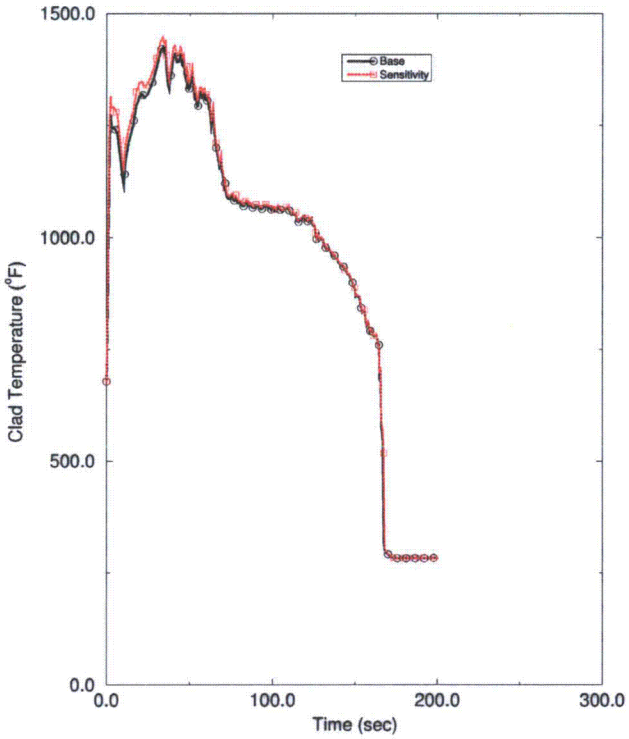
RODEX3 - Impact of increase of 300°F in Fuel Centerline Temperature

- Assessing PCT impact resulting from increasing the target centerline temperatures in the 59-case set by 300ºF.
- The Case 44 steadystate fuel centerline temperature is shown as an example.

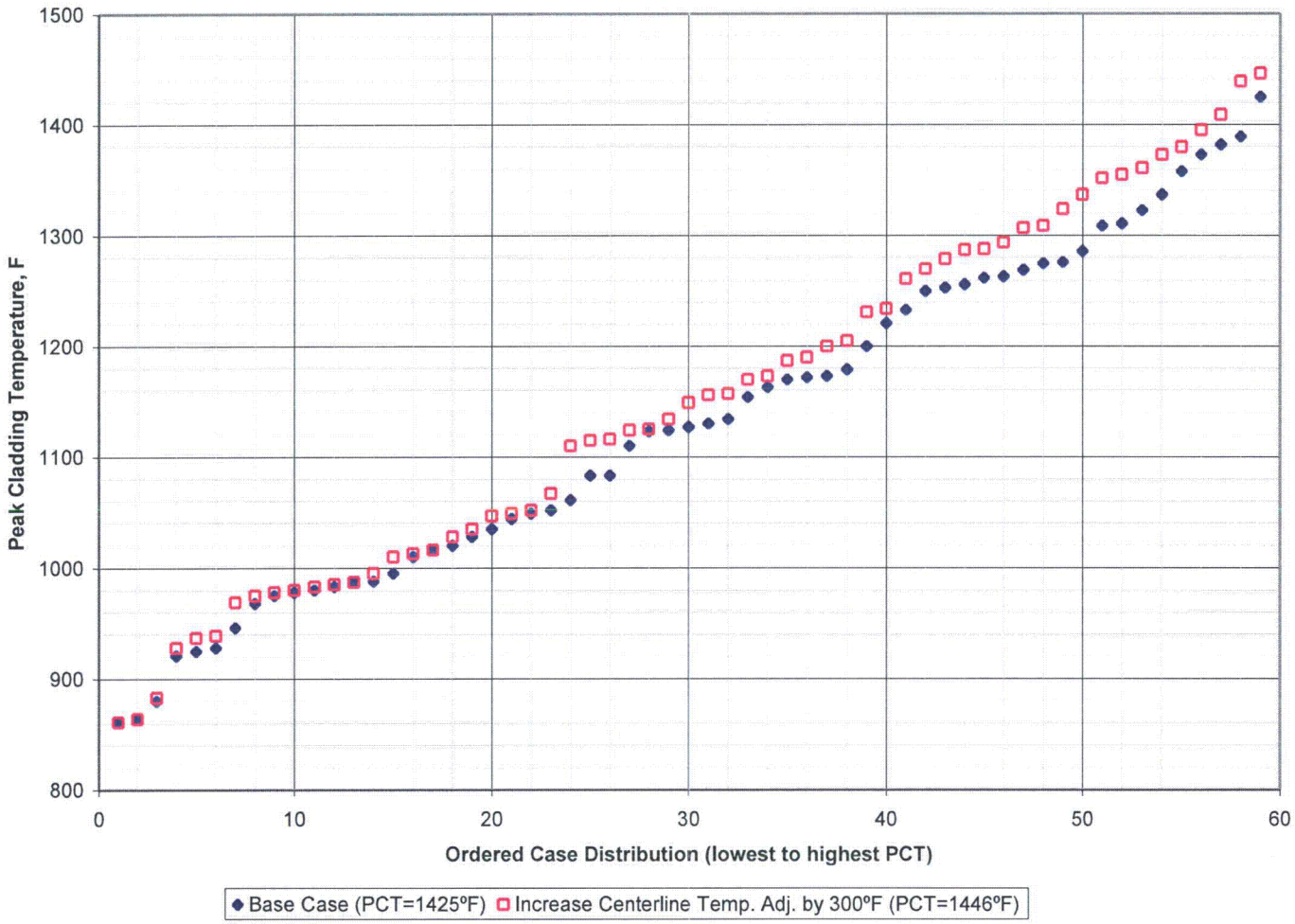


RODEX3 - Impact of increase of 300°F in Fuel Centerline Temperature

- This increased initial stored energy produces a higher clad temperature early in the transient: blowdown and refill
- The PCT in Case 44 occurs at the end of refill, so the difference in initial stored energy produces a higher PCT, as shown in the figure



RODEX3 - Sensitivity to 300°F Increase in Center Line Fuel Temperature



RODEX3 - Maintaining FUELK in Transient

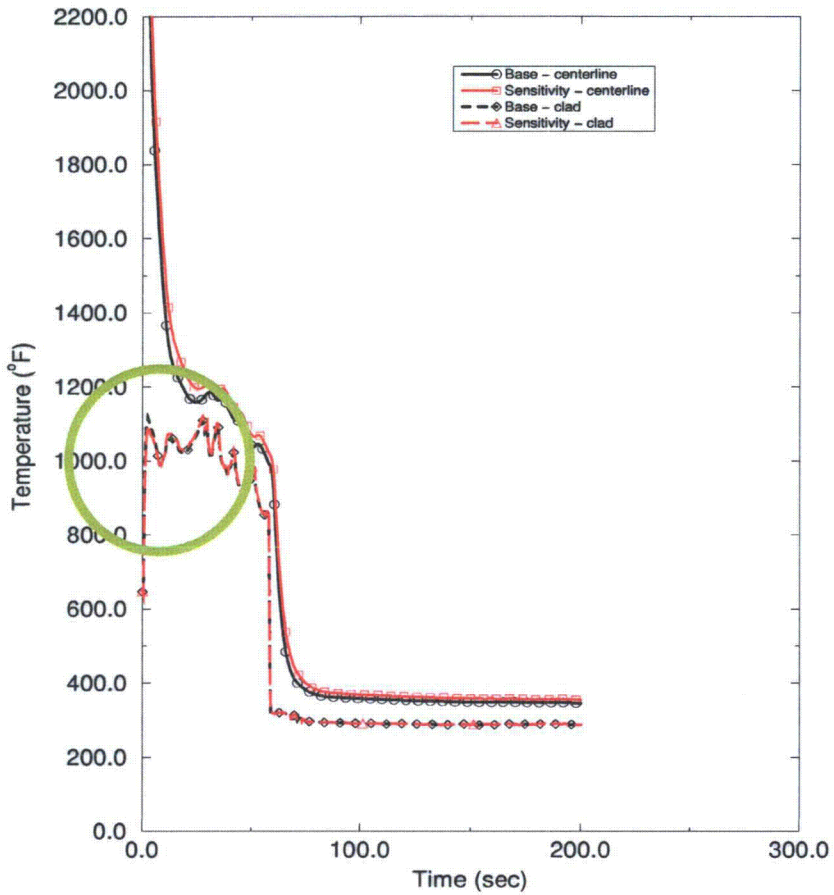
- NRC notes that the value of FUELK is set to unity for transient analyses even though it may have been less than unity for the steady state calculation. If the adjustment of FUELK for steady state calculation is to capture the thermal conductivity degradation due to burn-up, justify returning the value of FUELK to 1.0 for the four hot rods at the start of the transient.

Rodex3 - Maintaining FUELK in Transient

- Justify returning the value of FUELK to 1.0 for the four hot rods at the start of the transient
  - Resetting the FUELK multiplier to 1.0 in the transient, instead of using the calculated FUELK multiplier which is <1.0, promotes the rapid release of the fuel rod stored energy.
  - For a 59-case RLBLOCA analysis where the PCT occurs during blowdown, resetting the FUELK multiplier to 1.0 would be conservative in terms of the PCT calculation.

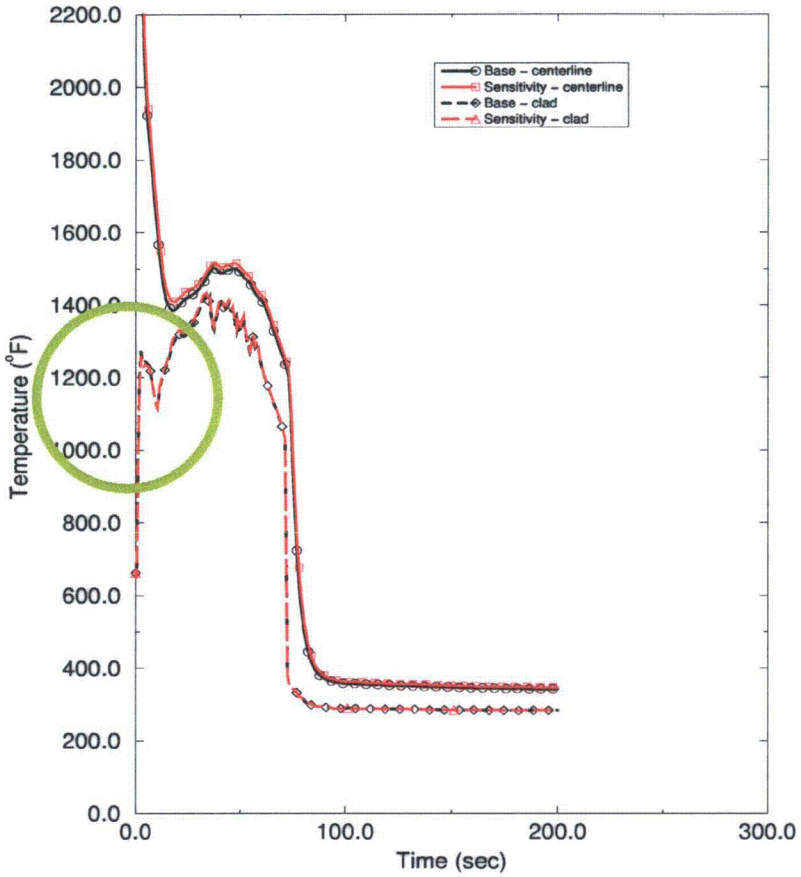
Rodex3 - Maintaining FUELK in Transient

Case 33 – PCT Shifts to Blowdown

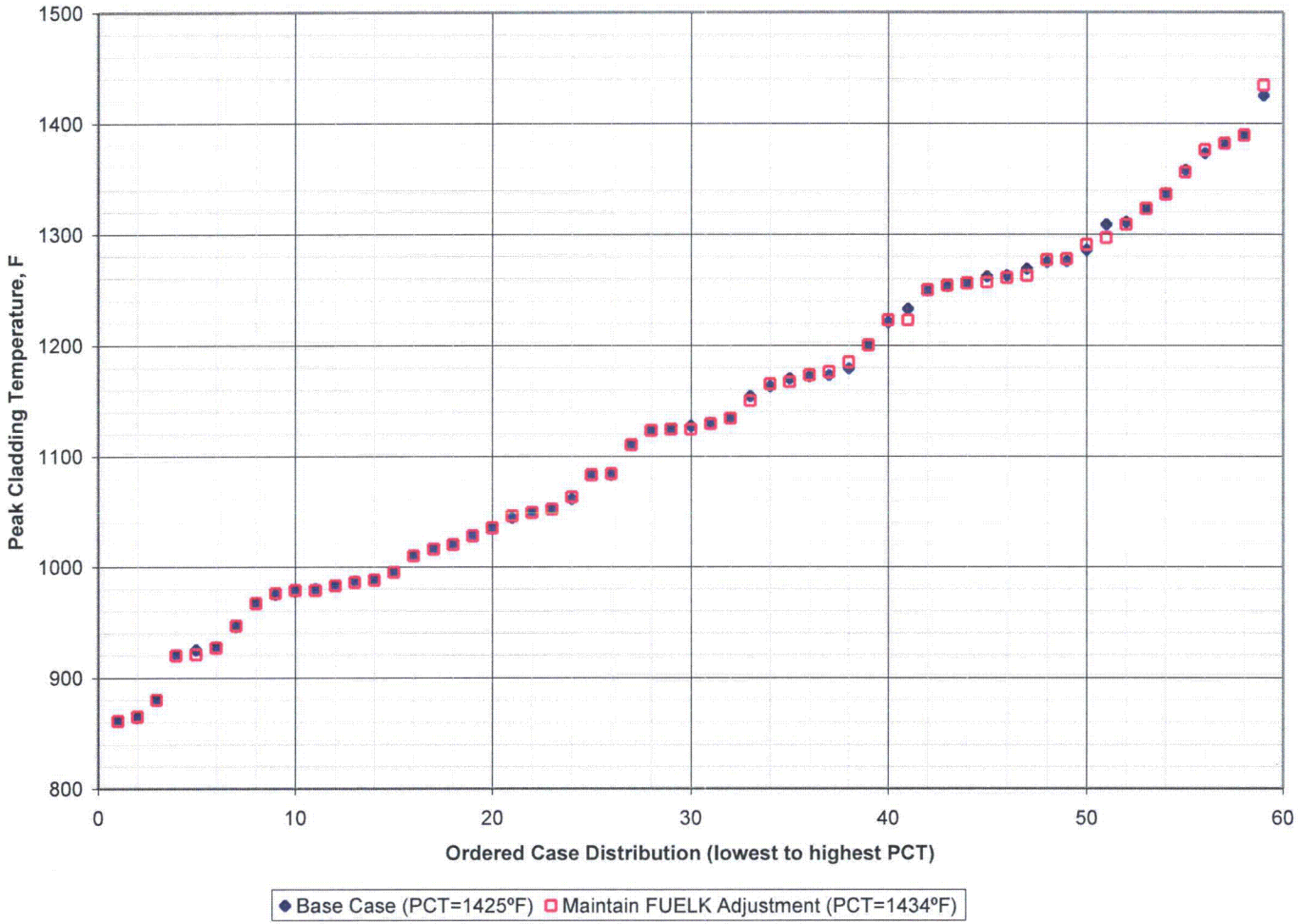


Rodex3 - Maintaining FUELK in Transient

Case 44



RODEX3 - Maintaining FUELK in Transient – Sorted Results for 59 Cases



RODEX3 Topics - Average Core

- Adapt model to reasonable average core representation
  - Second pin in average core region
    - One pin modeling fresh fuel
    - One pin modeling once burned fuel
  - Periphery region modeled as twice burned fuel
- Impact on results is small and variable
  - In case sets that increase average core energy, some cases increase PCT some cases decrease PCT
  - Studies To- Date Indicate Impact Under 50 F
- Recommend no change in methodology

RODEX3 Topics Conclusion

- RODEX3 can be adjusted to available data
- Additional adjustment possible
- PCT impact is approximately 50 F
  - Not required if adjustment factored into FUELK
- FUELK can be maintained during the transient
- Average core modeling to be decided in October

Lower Plenum Filling Issue

- **NRC Concern**
  - Reflood begins before lower plenum (LP) is full
  - Based on void distribution in LP and core at the start of reflood for the EPR RLBLOCA limiting case (No. 44)

- **AREVA Assessment**
  - In spite of LP not being full at the start of reflood, S-RELAP5 calculates the start time of reflood correctly-to-conservatively
  - Based on detailed evaluation of the liquid distribution in the primary system

Lower Plenum Refill - Presentation Objective

- **Justify the timing of the start of reflood calculated by S-RELAP5 for U.S. EPR RLBLOCA**
  - Experimental Observations
  - System Code Limitations
  - MPR Correlation and its use in RELAP5/MOD2-B&W Appendix-K Based Evaluation Model
  - S-RELAP5 Benchmarks
  - EPR Case-44 Evaluation
  - U.S. Summary

Lower Plenum Refill - Presentation Outline

- The flow phenomena in the downcomer and lower plenum during the end-of-blowdown and refill period
  - UPTF Integral and Separate Effect Tests
  - 2D/3D Program Conclusions
  - S-RELAP5 Benchmarks
  - Evaluation using U.S. EPR Limiting Case-44
- Summary

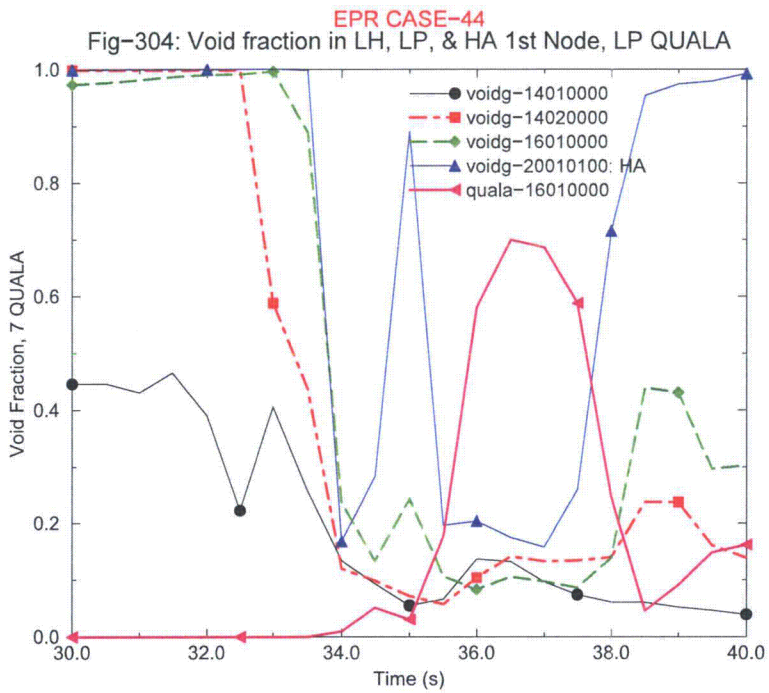
Lower Plenum Refill – Vessel Noding

Lower Plenum Refill – Vessel Noding

- Lower plenum noding

Lower Plenum Refill - Void Distribution at Start of Reflood

- **Void distribution in LH, LP, 1st core node, air quality in LP for EPR case-44**



Core reflood begins before LP ~ full, which is non-conservative.

Steam-air mixture flows down during refill – which possibly is non-physical

Lower Plenum Refill - UPTF Tests

- Under the 2D/3D program, several separate and integral tests were conducted in the Upper Plenum Test Facility (UPTF) to investigate ECC penetration and counter-current flow phenomena in the downcomer of a PWR during the end-of-blowdown (EOB) and refill portions of a LOCA

- Specific Test #s : 4, 5, 6, 7,and 27

- Facility scaling: UPTF:EPR is ~ 1: 1.3

Lower Plenum Refill - UPTF Tests
(continued)

- UPTF Integral Test 4 Phase A: Fluid sub-cooling contour plot at 40s

Lower Plenum Refill - UPTF Tests
(continued)

- UPTF Integral Test 4 Phase A: Fluid sub-cooling contour plot at 42s

[ ]

Lower Plenum Refill - UPTF Tests (continued)

- UPTF Integral Test 4 Phase A: Fluid sub-cooling contour plot at 46s

Lower Plenum Refill - UPTF Tests (continued)

- UPTF Integral Test 4 Phase A: Fluid sub-cooling contour plot at 49s

Lower Plenum Refill - UPTF Tests (continued)

- UPTF Integral Test 27 Phase A, Run 256: DC & LP Level (from vessel bottom).

Difference in levels
~ 1.0 m during LP refill

Lower Plenum Refill - UPTF Tests (continued)

- **Conclusions:**
  - There is no actual " end-of-bypass" period
  - Highly separated flow pattern in downcomer during the "refill" phase.
  - ECC flow from the two intact loops away from the broken loop falls down to LP like a "plume" with very little resistance.
  - Difference in liquid levels between LP and downcomer ~ 1.0 m during the LP refill.
  - As a result of these tests, the CSAU defined the "refill" period as the time from the start of accumulator discharge to the start of core flooding

Lower Plenum Refill
2D/3D Program Conclusions (continued)

- LP mass inventory in UPTF Integral Test 4A & CCTF Tests
  - Scale effects

Pressure ~ 800 kPa

Lower Plenum Refill
2D/3D Program Conclusions

- **2D/3D Program conclusion from these and other scaled tests as well as evaluations using TRAC code**
  - **DC flow behavior is highly multi-dimensional**
    - During high steam up-flow (~ > 320 Kg/s) period partial delivery from the two loops away from the broken loop (BL), and complete bypass from loop close to BL
    - For relatively low steam up-flow (~ < 100 Kg/s), completely delivery from the two loops away from BL, and partial delivery from loop close to BL
    - ECC delivery to DC in an intermittent manner consistent with the water plug movement in CL. Water falls down as a plume (water slug) -> relatively low resistance to reach the LP

Lower Plenum Refill System Code Limitations

- Difficult to simulate the observed multi-dimensional flow phenomena in downcomer during the LP refill phase using system codes like RELAP5, TRAC, or TRACE
- Simply adjusting interphase drag and/or nodalization is not always adequate
  - RELAP5/MOD2-B&W
  - TRAC-PF1/MOD2 & AREVA modification
  - S-RELAP5
- Fluid distribution between downcomer & LP might not agree with the experimental observation
- However, analytical treatments ensure the time of reflood is correctly or conservatively predicted
  - This is the important outcome for predicting PCT

Lower Plenum Refill - MPR Correlation

- Under 2D/3D program, MPR developed a CCFL correlation using the UPTF test data to calculate liquid down flow in downcomer during the refill phase.
  - AREVA used this correlation in RELAP5/MOD2-B&W based REG EM (deterministic) to calculate complete end-of-bypass.
  - The ACC injected water from end-of-bypass to EOB (break flow reversal) is added to the LP liquid inventory
  - Approved by the NRC

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6

- Run 135

[ ]

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6
(continued)

- Run 131

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6
(continued)

- Run 132

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6 (continued)

- Run 133

[ ]

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6
(continued)

- Run 136

Lower Plenum Refill
S-RELAP5 Benchmark of UPTF Test 6
(continued)

▶ Conclusions:

- ◇ Beginning of LP fill times are delayed by 1 to 5 sec
- ◇ LP fill rates are under predicted
- ◇ Results are consistent with code limitations in predicting the separated flow distributions in the downcomer as identified earlier.

Lower Plenum Refill - EPR Case-44

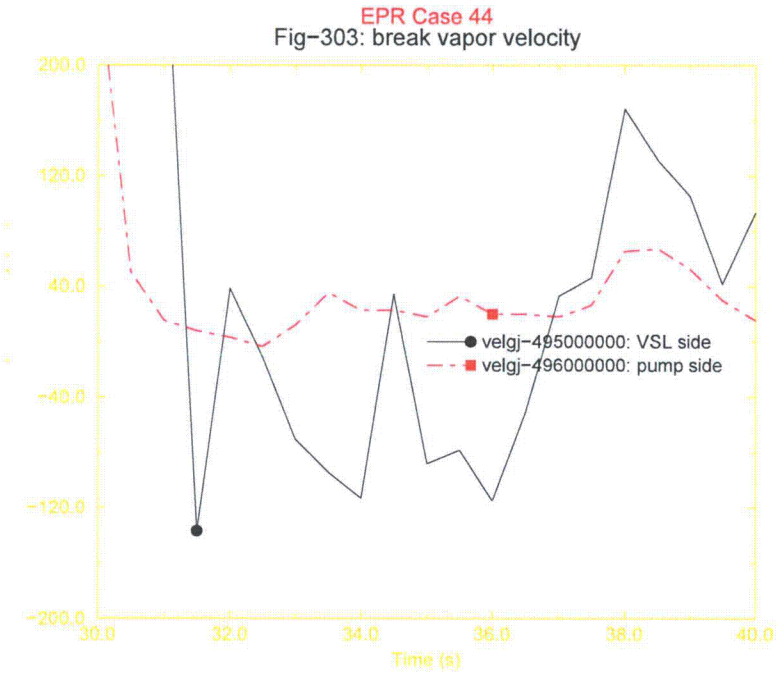
- **Vapor velocity at the break junctions.** End-of-blowdown at ~ 31.3 sec.

Using the 2D/3D summary
– water level in LP @ bottom of core barrel at EOB

Water level will reach at the bottom of core in two seconds after that

-> Bottom of Core recovery @ ~ 33.3 sec

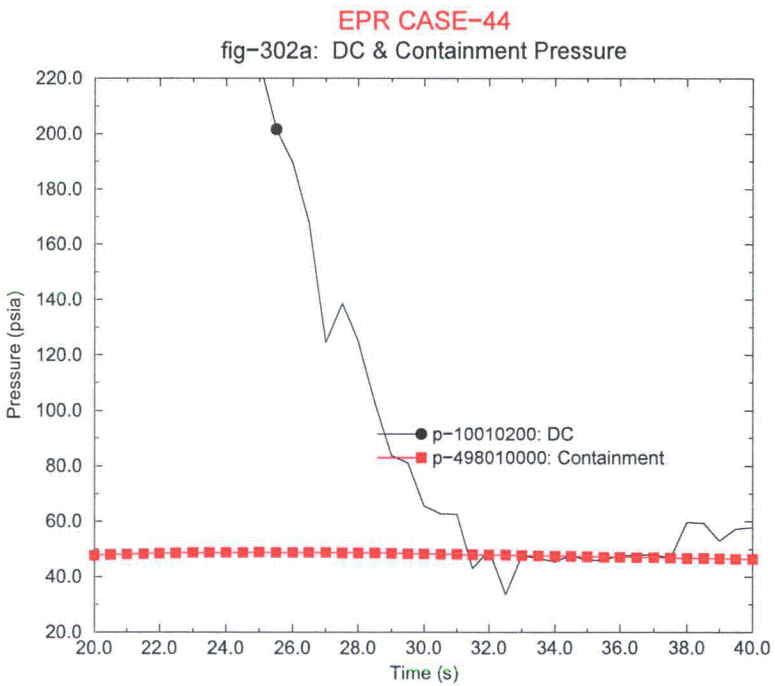
-> SRELAP5 conservatively predicts the BOCR time



Lower Plenum Refill - EPR Case-44 (continued)

- **Downcomer & containment pressure.**
  - **Pressure reaches 116 psia @ 28 sec, 174 psia @ 26 sec, containment pressure @ ~ 31.3 sec (consistent with break flow reversal)**

LP + LH height = 7.3 ft
Fill rate ~ 1.0 ft/s
Assuming LH liquid level ~ 2 ft, using the 2D/3D program pressure criteria, core reflooding begins between 31.3 & 33.3 sec



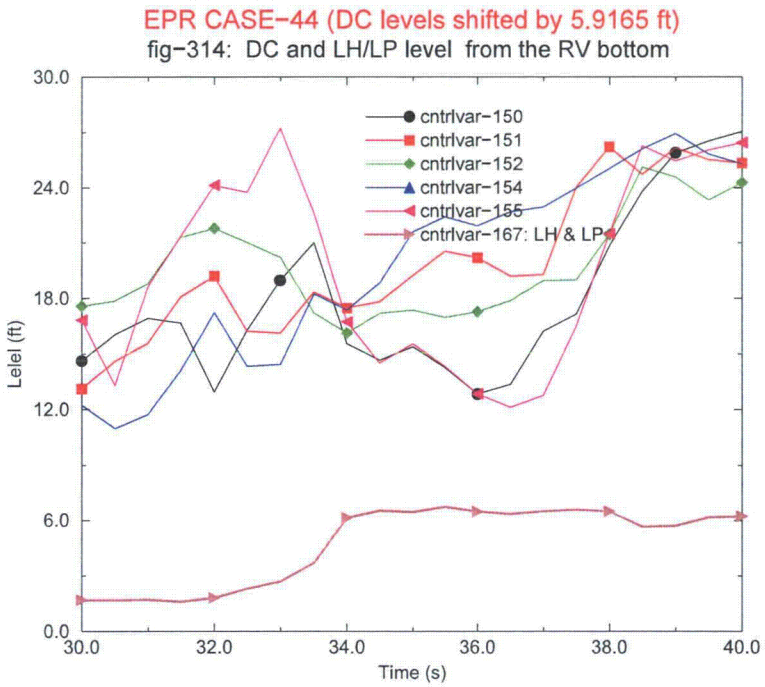
Lower Plenum Refill - EPR Case-44 (continued)

- **Downcomer and (LH + LP) liquid level (from the RV bottom).** The difference is ~ 15 ft -> much higher than observed in UPTF tests (~ 3 ft)

If the excess water from DC Is moved to LP, the LP level will be above the bottom of core barrel @ EOB.

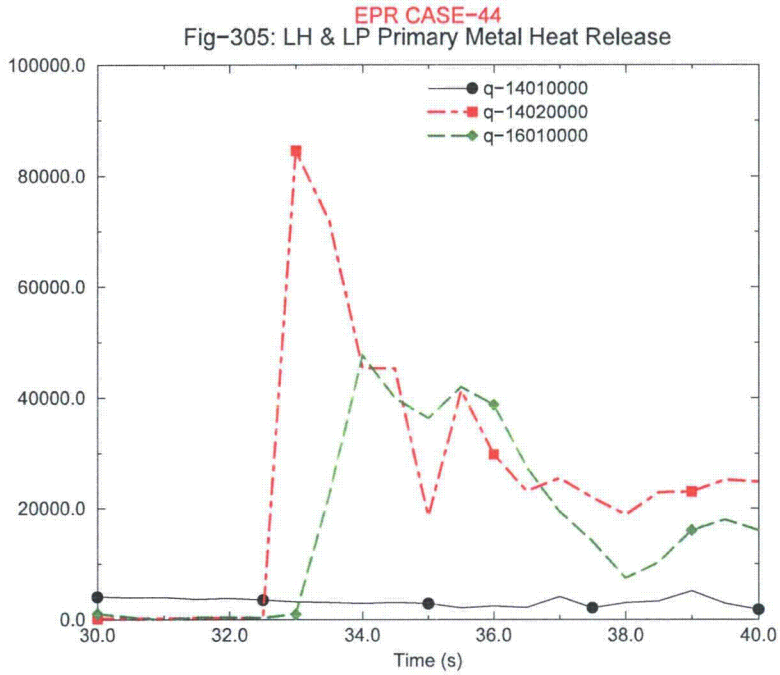
-> BOCR time ~ 33 sec

-> SRELAP5 conservatively predicts the BOCR time



Lower Plenum Refill - EPR Case-44 (continued)

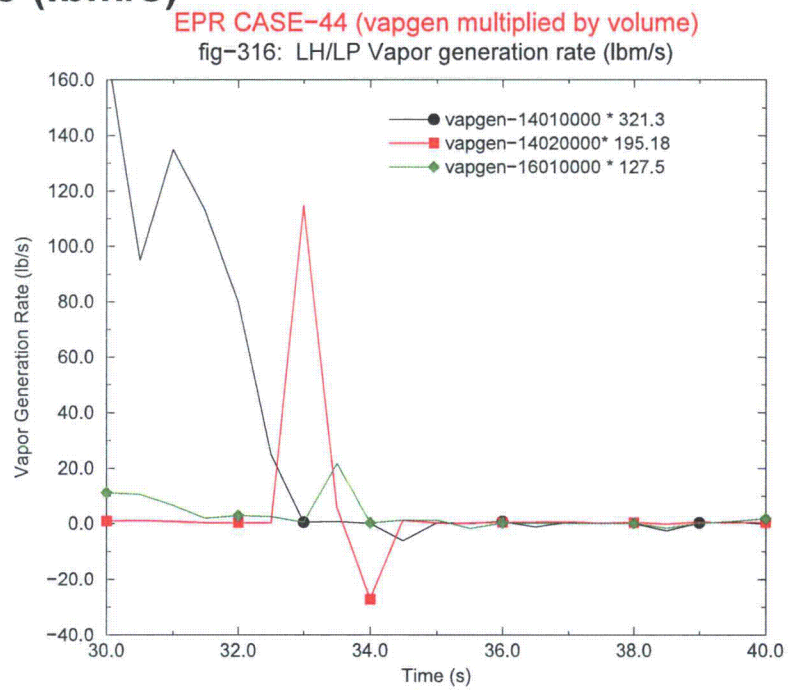
- LP & LH primary metal heat release



Lower Plenum Refill - EPR Case-44 (continued)

- **LP & LH Vapor Generation Rate (lbm/s)**

This vapor generation will cause frothing in LP -> water will get into the core before LP is filled with water

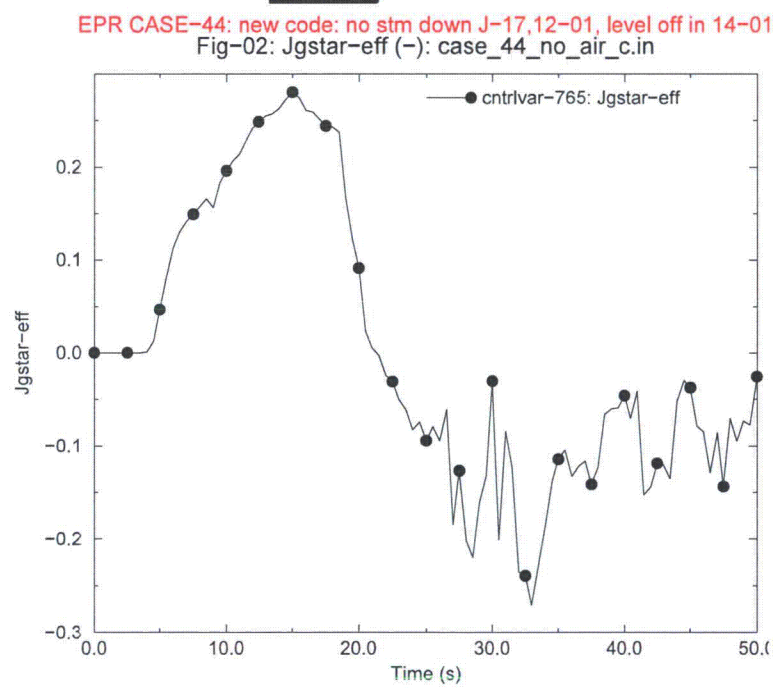


Lower Plenum Refill - EPR Case-44
(continued)

- **MPR CCFL correlation**

Complete end-of-bypass when

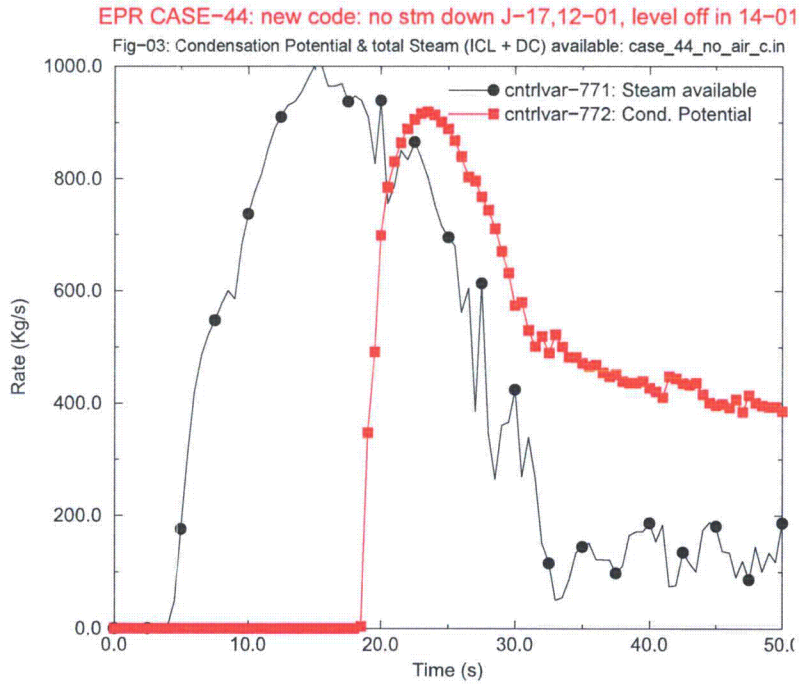
Becomes negative which occurs at ~ 21 sec. The LP fill rate is ~ 1.0 ft/s . Assuming water level in LP = 2ft at this time, the reflood begins at ~ 27 sec



Lower Plenum Refill - EPR Case-44 (continued)

- **Condensation potential and steam available**

Steam available = Intact Cold Leg + Downcomer steam flow
Condensation potential is 0.8 * steam that can condense on ACC flow.
At ~ 21 sec, condensation potential > steam available.
This is the complete end-of-bypass time
-> Reflood begins at ~ 27 sec

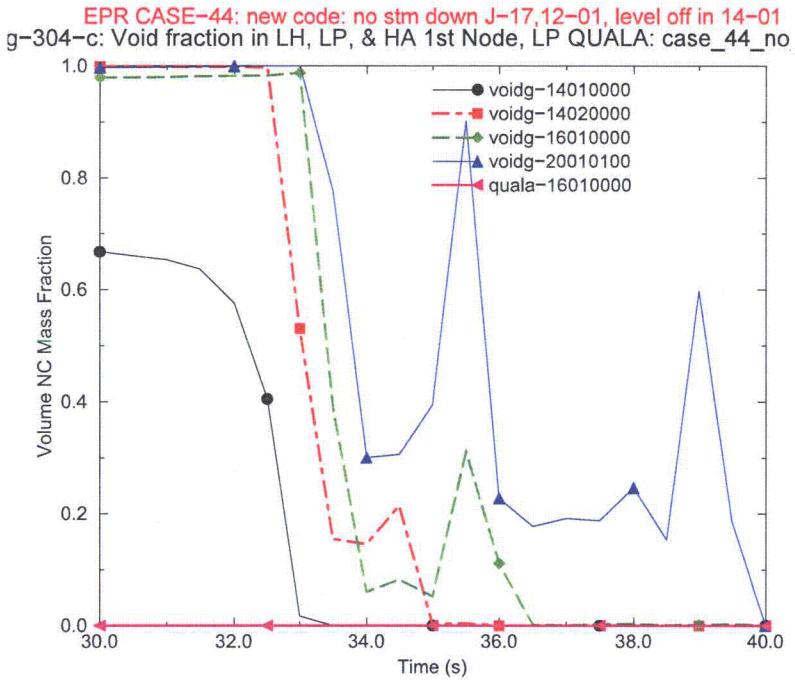


Lower Plenum Refill - EPR Case-44
(continued)

- **No steam & air down to LP/LH (special code)**

Reflood begins at ~ 33 sec vs. 33.5 sec as in the base case

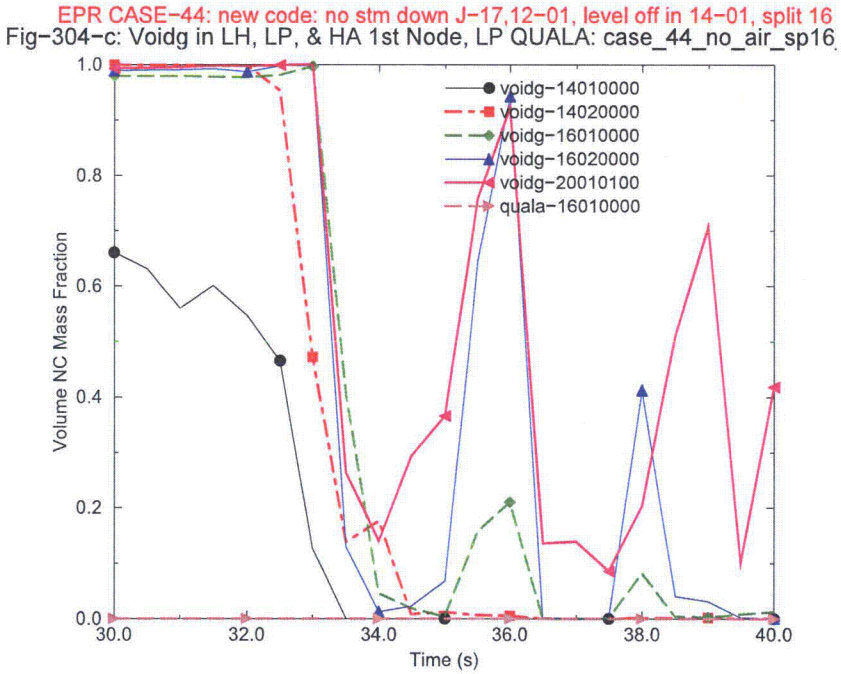
→As the DC draining resistance is reduced, the reflood start time reduces.



Lower Plenum Refill - EPR Case-44 (continued)

- No steam & air down + split LP node 16

Splitting of LP node 16 has no effect.



Lower Plenum Refill - EPR Case-44 (continued)

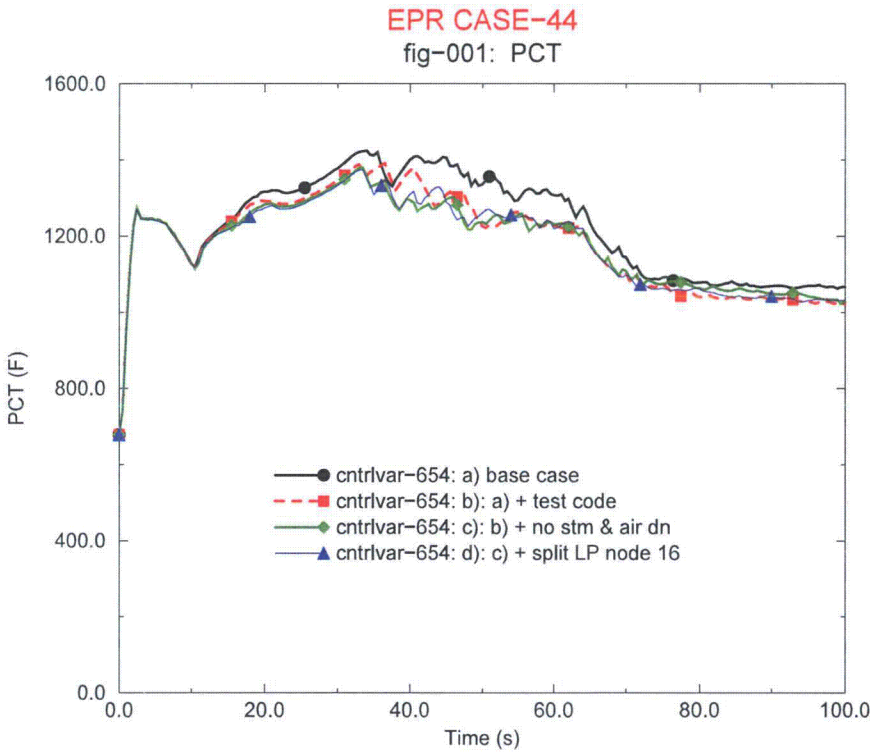
PCT reduces as DC draining is made more realistic.

Base S-RELPA5 Predicts conservative PCT

The effects wash out after the approximate time that the Accumulator empties.

Typically PCTs occur near the time the Accumulators empty.

Case-044 is atypical because PCT occurs just after BOCR.



Lower Plenum Refill - Summary

- S-RELAP5 conservatively calculates the timing of start of reflood in the U.S. EPR RLBLOCA cases
  - Justified using the UPTF integral and separate effect tests
  - If the fluid distribution between downcomer & LP is calculated correctly, the start of reflood is early by ~ 0.5 sec for Case-44
  - MPR CCFL correlation predicts beginning of reflood time ~ 6 sec earlier for Case 44
  - Not allowing steam & air down to LP, accelerates the start of reflood

DECAY HEAT

- NRC approval in Regulatory Guide 1.157
- 1979 ANS Standard and Uncertainty
- Energy per fission
- Sensitivity studies

Decay Heat
NRC Approval in Regulatory Guide 1.157

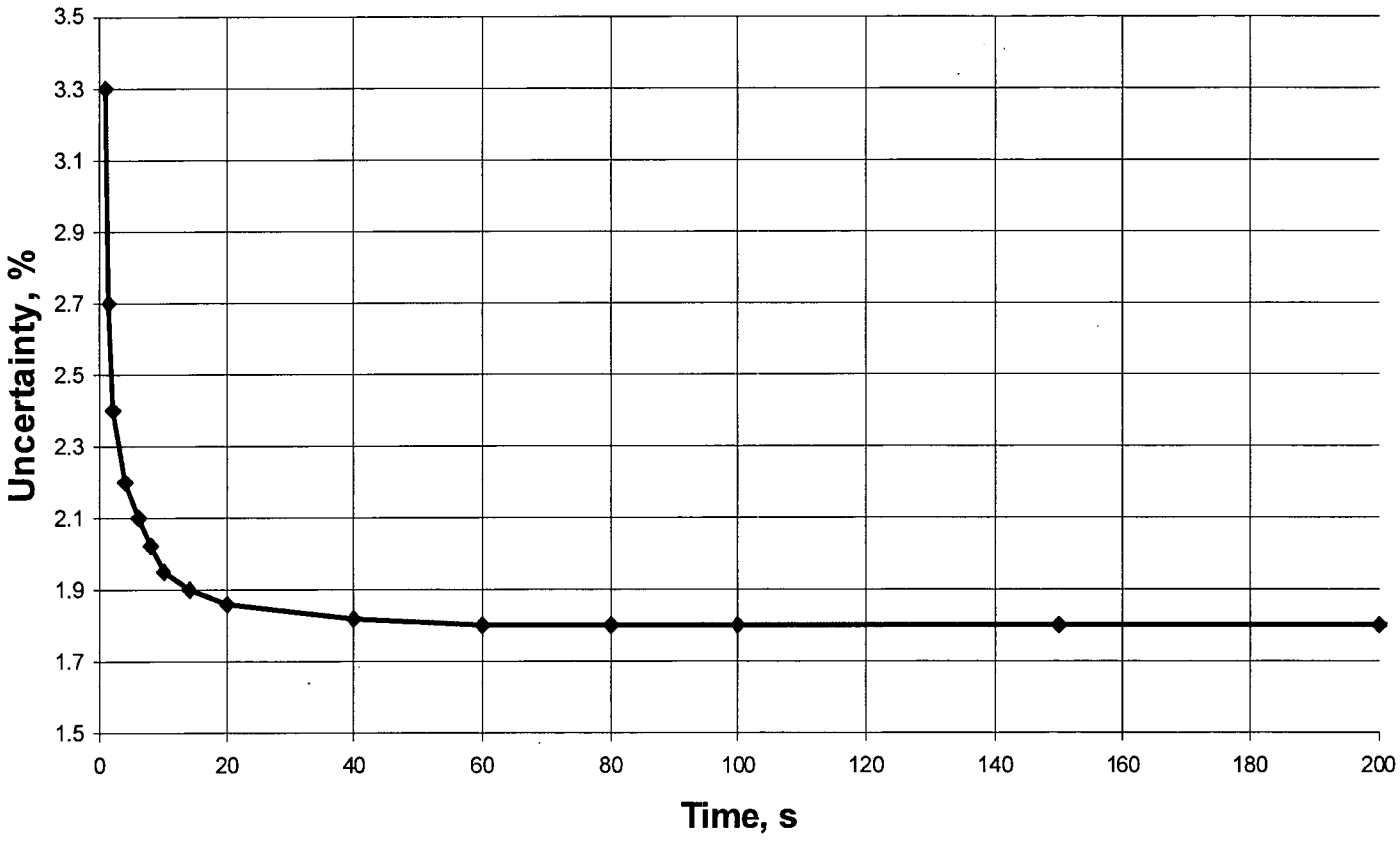
- The current revision of § 50.46 permits ECCS evaluation models to be fully "best-estimate" and removes the arbitrary conservatisms …
  - 1.157 Section B. "DISCUSSION"
- The heat generation rates from radioactive decay of fission products, including the effects of neutron capture, should be included in the calculation and should be calculated in a best-estimate manner. … The model in Reference 10 is considered acceptable for calculating fission product decay heat.
  - 1.157 Section C. "REGULATORY POSITION" 3.2.4 Fission Product Decay Heat
  - Reference 10 is the ANS 1979 Decay Heat Standard.

Decay Heat - 1979 ANS Standard and Uncertainty

Table 4
Tabular Data for Standard Decay Heat for Thermal Fission of ^{235}U and for Irradiation of 10^{13} Seconds

Time After Shutdown (s)	Decay Heat Power F(t,∞) (MeV/fission) (a)	One Sigma Uncertainty ΔF(t,∞) (MeV/fission)	One Sigma Uncertainty Percent
1.0000E+00	1.231E+01 (b)	0.040E+01	3.3
1.5000E+00	1.198E+01	0.032E+01	2.7
2.0000E+00	1.169E+01	0.028E+01	2.4
4.0000E+00	1.083E+01	0.023E+01	2.2
6.0000E+00	1.026E+01	0.021E+01	2.1
8.0000E+00	9.830E+00	0.198E+00	2.0
1.0000E+01	9.494E+00	0.187E+00	2.0
1.5000E+01	8.882E+00	0.170E+00	1.9
2.0000E+01	8.455E+00	0.159E+00	1.9
4.0000E+01	7.459E+00	0.137E+00	1.8
6.0000E+01	6.888E+00	0.125E+00	1.8
8.0000E+01	6.493E+00	0.118E+00	1.8
1.0000E+02	6.198E+00	0.112E+00	1.8
1.5000E+02	5.696E+00	0.103E+00	1.8
2.0000E+02	5.369E+00	0.097E+00	1.8
4.0000E+02	4.667E+00	0.083E+00	1.8
6.0000E+02	4.282E+00	0.076E+00	1.8
8.0000E+02	4.009E+00	0.071E+00	1.8

Decay Heat - 1979 ANS Standard and Uncertainty

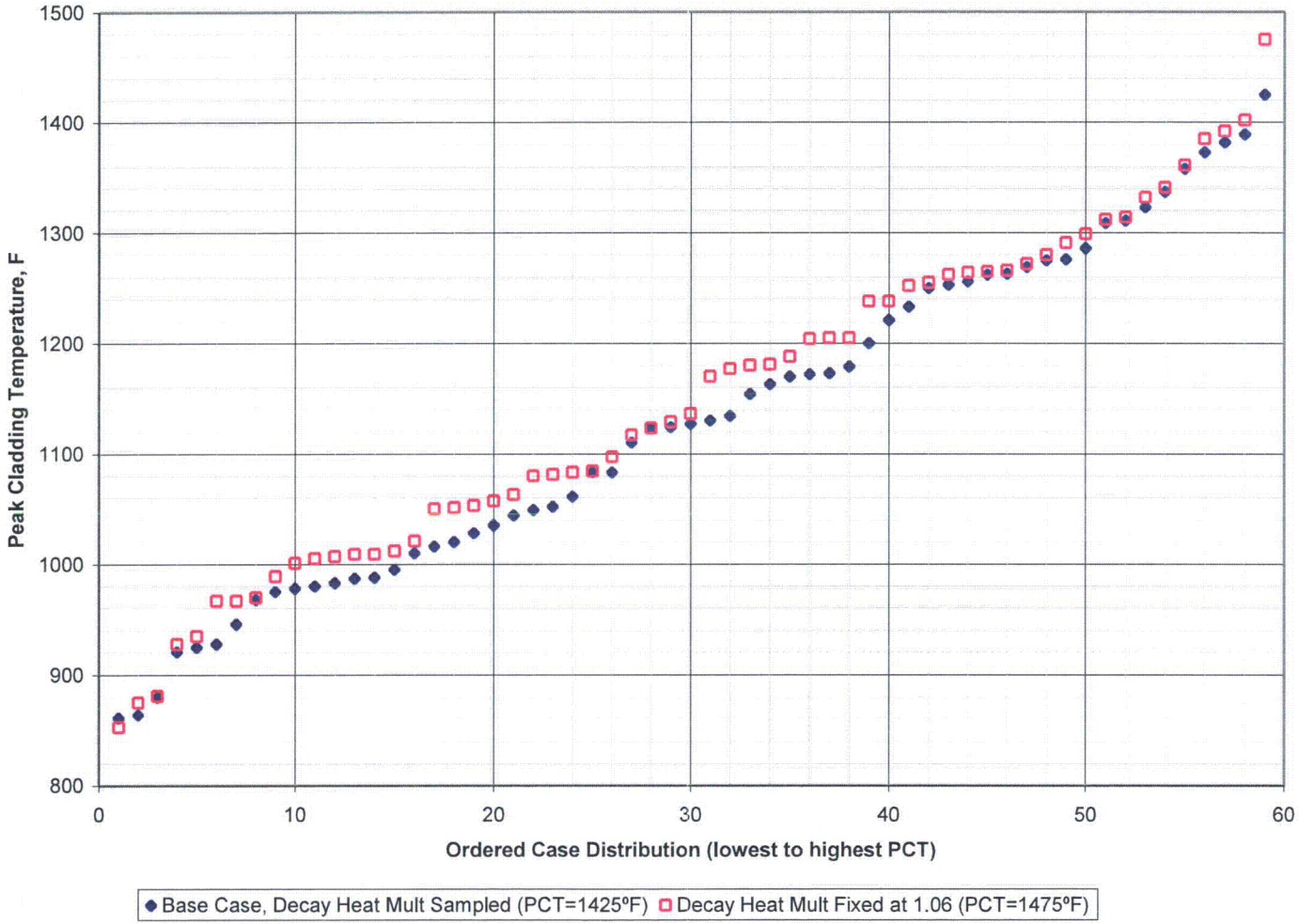


Decay Heat - Energy per Fission

▶ Assumed in RLBLOCA Decay Heat Application	200 Mev
▶ Appropriate for U235	~ 202 Mev
▶ Appropriate for U238	~ 205 Mev
▶ Appropriate for Pu239	~ 211 Mev
▶ Appropriate for Pu241	~ 214 Mev

- ▶ Fresh Fuel - only U235 and U238 - No Exposure
  - ◇ Minimum Margin > 1 %
- ▶ As exposure builds in
  - ◇ Margin Builds to Several Percent

Fixing Decay Heat Multiplier at 1.06 – Sorted Results for 59 Cases



Decay Heat - Conclusions

- The NRC has specified best estimate modeling for decay heat
- NRC approved ANS 1979 for use in BE LOCA
- Fuel isotopes with ANS 1979 standard conservatism in AREVA's approach